# Beamforming Performance Analysis for OFDM Based IEEE 802.11ad Millimeter-Wave WPANs

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$8^{th}$ International Workshop on
Multi-Carrier Systems and Solutions

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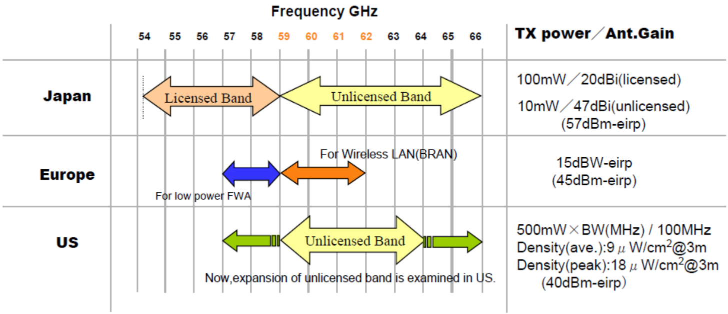
# Outline

# 60 GHz Frequency Band Allocation




- Large availability of 7 GHz unlicensed in worldwide
- Potentially small device components

# Overview of 60 GHz WPAN

## Standards over 60 GHz WPAN

- IEEE 802.15.3c
- WirelessHD
- WiGig
- ECMA-387
- IEEE 802.11ad

## Characteristics of 60 GHz millimeter-wave WPANs

- In-door (<10m)
- Uncompressed HDTV and high rate data transfer
- At least 1 Gbps throughput, 3-4 Gbps preferable

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   - Overview of Wireless Personal Area Network (WPAN)
   - IEEE 802.11ad Standard
2. System Model
   - Channel Frequency Response
   - Optimization Criteria
3. OFDM Based Beamforming
   - Subcarrier-wise
   - Symbol-wise
   - Hybrid
4. Numerical Results
   - Beamforming Gain
   - BER Performance
   - Link Throughput and Ranges

# Operating Modes

- Single Carrier: Low complexity and control information
- OFDM: High performance applications

Table: OFDM Modulation and Coding Schemes

| Modulation | Coding Rate | Coded Bits/Symbol | Data Bits/Symbol | Data Rate (Mbps) |
|---|---|---|---|---|
| QPSK | 1/2 | 672 | 336 | 1386.00 |
| QPSK | 5/8 | 672 | 420 | 1732.50 |
| QPSK | 3/4 | 672 | 504 | 2079.00 |
| 16-QAM | 1/2 | 1344 | 672 | 2772.00 |
| 16-QAM | 5/8 | 1344 | 840 | 3465.00 |
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| 16-QAM | 13/16 | 1344 | 1092 | 4504.50 |
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# MIMO Communication System

Let $y_m$ be the received decision baseband signal for the *m*th subcarrier

$$y_m = \widetilde{H}_m x_m + n_m, \qquad m = 1, \ldots N$$

where $\mathbf{x}_m$ is the transmitted data symbol, $\mathbf{n}_m$ is the Gaussian noise vector with zero mean and variance $\sigma^2$, $\boldsymbol{N}$ is the number of subcarriers, and $\widetilde{H}_m$ represents the frequency response of the equivalent channel matrix for the *m*th subcarrier after beamforming, which is given by:

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# Choose the Optimal Weight Vectors

## Optimization Criteria

- Max-codeword-distance
- Max-BER
- Max-mutual-information
- Max-effective-SNR

$$\gamma_{eff} = -\beta \ln \left[ \frac{1}{N} \sum_{m=1}^{N} \exp\left(-\gamma_m/\beta\right) \right]$$

where $\gamma_m$ is the symbol SNR experienced on the $m$th subcarrier, $\beta$ is a parameter dependent on MCS.

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$$\gamma_m = \frac{E\left[\left|c^H H_m w x_m\right|^2\right]}{E\left[\left|n_m\right|^2\right]} = \frac{\left|c^H H_m w x_m\right|^2}{M_t M_r \sigma^2}$$

where $M_t$ and $M_r$ are the number of antenna elements at the transmitter and the receiver respectively. When normalized, $w^H w = M_t$ and $c^H c = M_r$.

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# Outline

# Maximize the Received SNR on Each Subcarrier

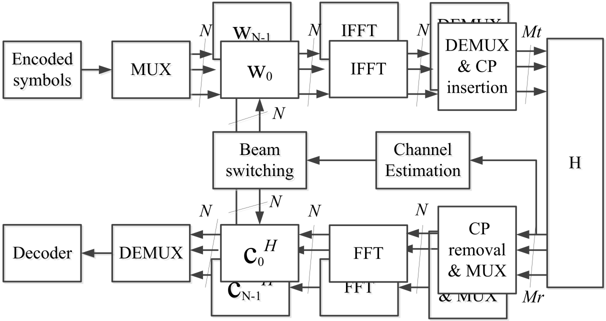


Figure: Block diagram of subcarrier-wise beamforming

$$\gamma_{eff,subcarrier} = -\beta \ln \left[ \frac{1}{N} \sum_{m=1}^{N} \exp\left( -\frac{\max_{c,w} \left| c^H H_m w \right|^2}{\beta M_t M_r \sigma^2} \right) \right]$$

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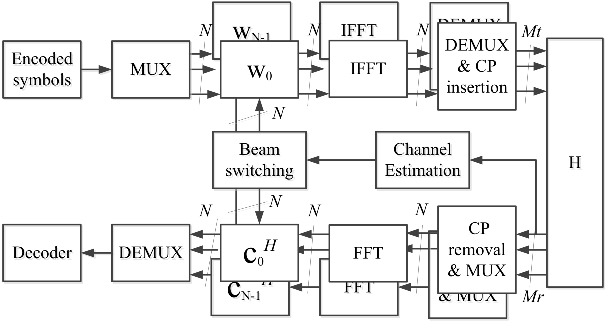


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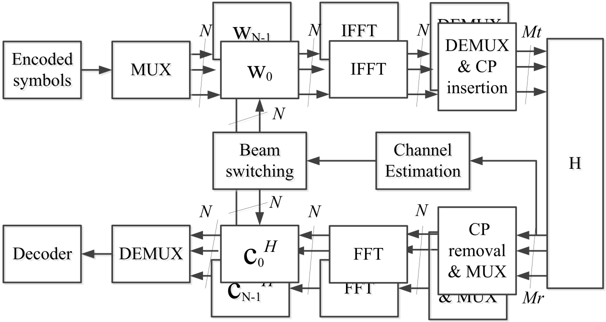


Figure: Block diagram of subcarrier-wise beamforming

## Optimal but not practical

- Need full channel state information
- Requires one FFT/IFFT processor per antenna

# Outline

# Each Subcarrier Applies the Same Weight Vector

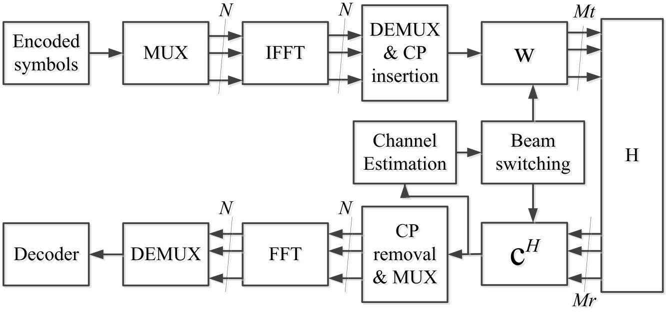


Figure: Block diagram of symbol-wise beamforming

## Pre-defined beam codebook

- Full channel state information is not required
- Depends on the number of antenna elements and beams

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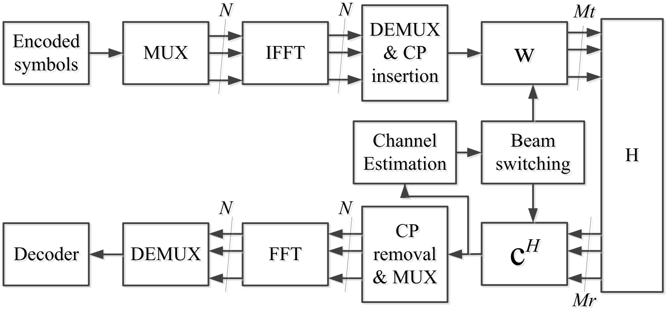


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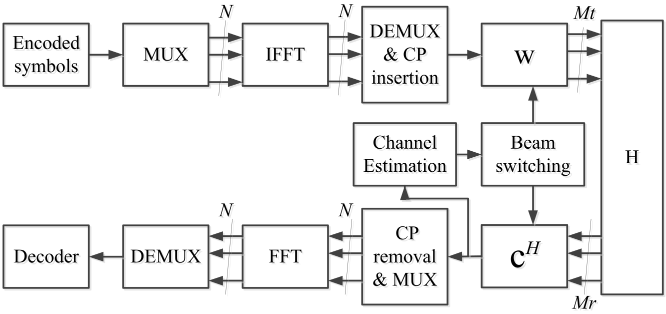


Figure: Block diagram of symbol-wise beamforming

$$\gamma_{eff,symbol} = \max_{c,w \in C} (-\beta) \ln \left[ \frac{1}{N} \sum_{m=1}^{N} \exp\left( -\frac{\left| c^H H_m w \right|^2}{\beta M_t M_r \sigma^2} \right) \right]$$

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# Compromise the complexity and performance

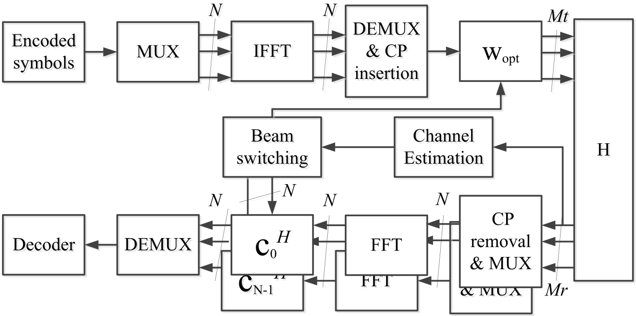


Figure: Block diagram of hybrid beamforming

## Symbol-wise at Tx, and subcarrier-wise at Rx

- Optimal each receiver steering vector
- Also use pre-defined codebook

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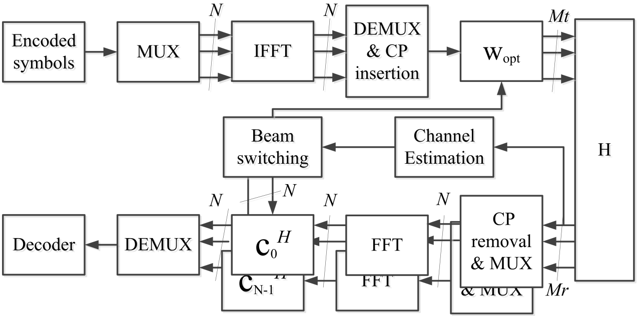


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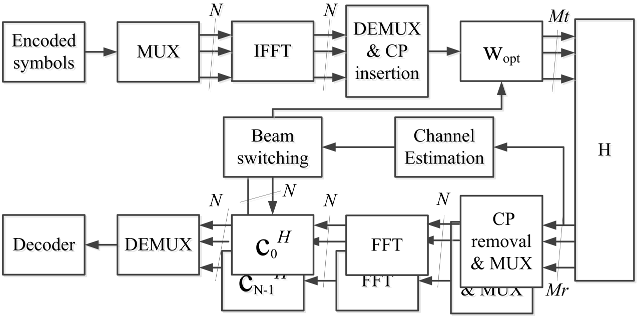


Figure: Block diagram of hybrid beamforming

$$\gamma_{eff,hybrid} = \max_{w \in C} (-\beta) \ln \left[ \frac{1}{N} \sum_{m=1}^{N} \exp \left( - \frac{\left| c^H H_m w_{opt} \right|^2}{\beta M_t M_r \sigma^2} \right) \right]$$

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# Preliminaries

## System assumptions

- $N$=512 OFDM subcarriers
- 1D half wavelength isotropic radiators
- $M = M_t = M_r$ antenna elements

## Channel assumptions

- 60 GHz channel models
- Both LOS and NLOS

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# LOS Scenario

## Evaluate beamforming performance

$$G = \frac{\gamma_{eff,beamforming}}{\gamma_{eff,SISO}}$$

- Beamforming gain has a bound when single path exists
- The performance difference is not noticeable, because the LOS component exists

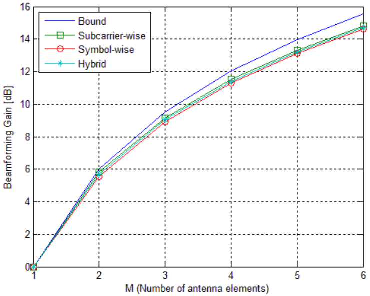


Figure: Beamforming gain with LOS

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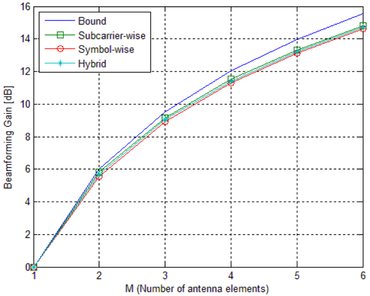


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# NLOS Scenario

## Evaluate beamforming performance

$$G = \frac{\gamma_{eff,beamforming}}{\gamma_{eff,SISO}}$$

- Subcarrier-wise is the best, hybrid is the next and symbol-wise is the worst
- The more antenna elements, the higher improvement can be achieved by hybrid beamforming

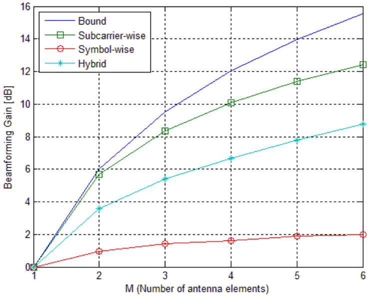


Figure: Beamforming gain with NLOS

# Outline



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# Bit Error Rate

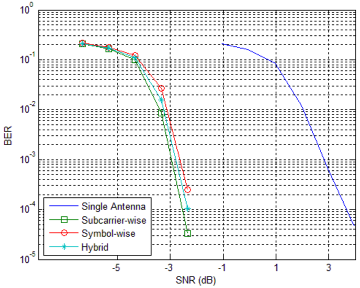


Figure: BER for QPSK 1/2 with LOS

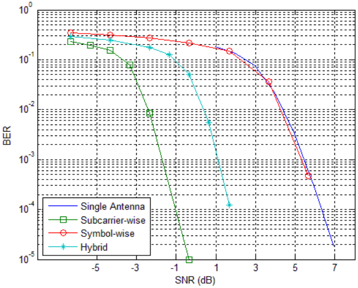


Figure: BER for QPSK 1/2 with NLOS

- A 2-by-2 antenna system is assumed
- The simulated BER performance verified the numerical results

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# Outline

# Link Throughput in LOS

## Link Adaptation Scheme

- The PHY mode with highest throughput will be selected:

$$Throughput = R(1 - PER)$$

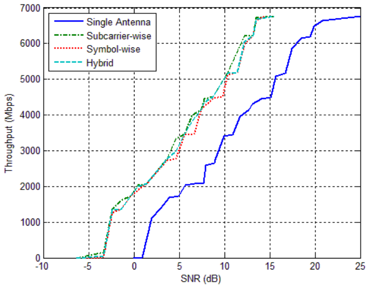


Figure: Link throughput with LOS

- The throughput envelop is the ideal adaptive MCS based on the optimum switching point
- At a certain SNR, beamforming systems offer higher throughput than SISO

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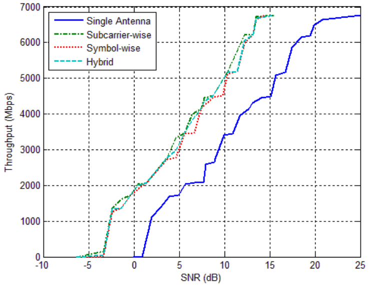


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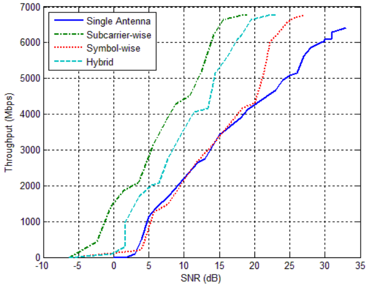


Figure: Link throughput with NLOS

- Beamforming schemes do not improve the peak error-free throughput
- More gain can be achieved for very high throughput (>4500 Mbps)

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# Operation Range in LOS

## Path Loss Model

$$PL(dB) = A + 20\log_{10}(f) + 10n\log_{10}(D)$$

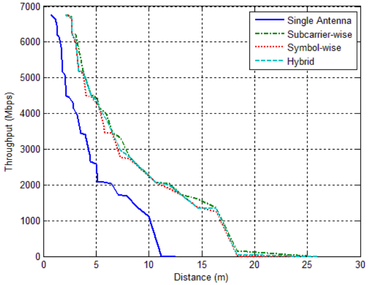


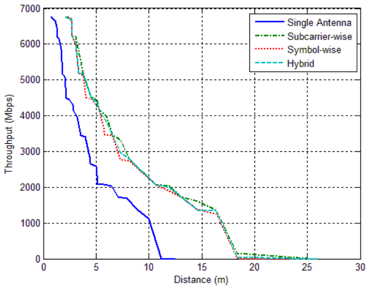

Figure: Operation range in LOS

- The system operates at its maximum throughput when the device are close
- Adaptively switch to the lower speed when a device moves further away

# Operation Range in LOS

## Link Budget Model

$$P_T - PL \geq kTB + NF + ReceiverSNR$$

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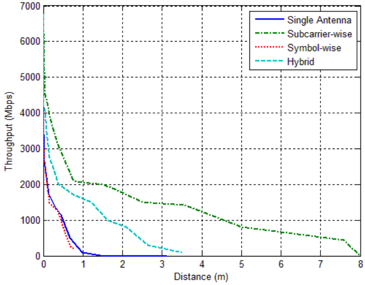


Figure: Operation range in NLOS

- The SISO system could not provide service beyond 1m
- Subcarrier-wise and hybrid beamforming extend the achievable range significantly

# Summary

- A performance evaluation of three types of beamforming schemes over the OFDM based 60 GHz WPAN are studied;
- Beamforming schemes increase the system performance significantly;
- In NLOS, hybrid beamforming provide considerable improvements while maintaining reasonable hardware complexity

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# For Further Reading I

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# Thank you! and Questions?

or Email to <x.zhu@Bristol.ac.uk>